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A note on bluff body vortex formation

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Green & Gerrard (1993) have presented in a recent paper the results of experiments to measure the distribution of vorticity in the near wake of a circular cylinder at low Reynolds numbers (up to $Re = 220$). They also compared the various definitions of the vortex formation region length which have been proposed by Gerrard (1966), Griffin (1974), and others for both high and low Reynolds numbers. The purpose of this note is to expand the work of Green & Gerrard, and to further their proposition that the end of the vortex formation region at all Reynolds numbers mark both the initial position of the fully shed vortex and the location at which its strength is a maximum. The agreement discussed here between several definitions for the formation region length will allow further understanding to be gained from investigations of the vortex wakes of stationary bluff bodies, and the wakes of oscillating bodies as well.

1. Introduction

Vortex streets are formed in the wakes of bluff bodies over a wide range of Reynolds numbers, from approximately 50 to 10^6 and even higher. The physics of vortex street formation and the near-wake flow has been the focal point of interest for many experimental studies. A recent example is the investigation of the mechanics of bluff body vortex formation and vorticity generation by Green & Gerrard (1993), which advances the earlier work of Gerrard (1966, 1978) and of Bloor & Gerrard (1966). One reason for this continued interest is the importance of knowing how the mean and fluctuating fluid forces are generated on the body due to the vortex shedding. Another is the perceived influence or 'footprint' of the near-wake flow in the eventual evolution of the overall middle- and far-wake flow fields (Cimbala, Nagib & Roshko 1988). Recent advances in stability theory and related experiments have shown that the vortex formation region is one of global absolute instability (Rockwell 1990; Schumm, Berger & Monkewitz 1994). These findings by several investigators have fundamentally changed our perception of the near-wake physics.

The purpose of this note is to discuss the various lengthscales of the bluff body near wake which have been cited by Green & Gerrard (1993), and others previously. Then a comparison is made between near-wake measurements of the vortex formation region and the related velocity field. This comparison allows the vortex formation and vorticity generation processes of the near wake to be reconciled further at both high and low Reynolds numbers.

Improvements in both computing power and numerical simulation capabilities now complement the many experiments already performed and allow the bluff body flow field to be computed to very high resolutions in both two and three dimensions. Some recent examples are given by the work of Karniadakis & Triantafyllou (1989, 1992), Hall & Griffin (1993), and Meneghini & Bearman (1993).

2. Bluff body vortex formation

The flow in the vortex formation region of a bluff body is generally agreed to be important to the overall development of the near-wake flow, and to the ensuing physical evolution of the wake. This is the region of the flow where vortex shedding is initiated at all Reynolds numbers. A visualization of the vortex formation region for a circular cylinder is shown in figure 1. Here the vortex formation region length is measured from the centre of the cylinder. This photograph of the wake at $Re = 200$ illustrates clearly the phenomenological model originally proposed by Gerrard (1966). The clarity and two-dimensionality of the vortex formation region are increased by the stabilizing crossflow oscillations of the cylinder at this Reynolds number.

According to Gerrard, the growing vortex is fed by circulation from the separated shear layer until it becomes strong enough to roll up and draw the opposing shear layer across the wake. This vorticity of opposing sign cuts off further circulation to the growing vortex, which then is shed and moves away downstream. There is a delicate balance between the vorticity which is (*a*) entrained into the growing vortex, (*b*) entrained into the separated shear layer, and (*c*) cancelled in the next half of the shedding cycle. The entrained vorticity (*b*) plays a key role in Gerrard's model. This is the high-*Re* mechanism discussed by Green & Gerrard (1993).

The high and low Reynolds number ranges vary somewhat as they are defined in the literature, for example, by Roshko (1954, 1955), Gerrard (1966, 1978), and Williamson (1988, 1989). Generally speaking, the laminar range extends to $Re = 200$, a transitional range from $Re = 200$ to 350, and the high range of *Re* above 350. Several definitions of the vortex formation region length, or its extent in the streamwise direction, have been proposed over the past forty years:

(i) the minimum of the mean pressure on the wake axis, or centreline;

(ii) the maximum of the wake velocity fluctuation at the fundamental shedding or Strouhal frequency, off the wake centreline;

(iii) the maximum of the wake velocity fluctuation at twice the shedding frequency, on the wake centreline;

(iv) the minimum cross-stream or lateral spacing, close to the body base region, of the maxima of the velocity fluctuation field.

The first definition of the formation region given here was proposed by Roshko (1954, 1955), based upon measurements of the near-wake pressure and velocity fields for several bluff bodies at high Reynolds numbers (above 350). The third was proposed originally by Gerrard (1966), for the same high Reynolds numbers, and by Griffin (1974) for low Reynolds number wakes. The second and fourth definitions were introduced by Schaefer & Eskinazi (1959) for circular cylinder wakes at low Reynolds numbers, and by Bearman (1965) for blunt-based bluff bodies at high Reynolds numbers.

The wake width d' at the end of the vortex formation region (the cross-stream distance, given by (iv), between the maxima of u_{rms} at that streamwise location) is tied closely to the base pressure coefficient $-C_{pb}$ or the related velocity ratio $K = U_b/U$, as shown by Roshko (1954, 1955). Here the separation velocity U_b is defined in terms of the base pressure coefficient by $U_b = (1-C_{pb})^{1/2}\,U$. In general, the bluffness of a given body cross-section is represented by a wider wake width d', with correspondingly lower (more negative) base pressure and higher velocity ratio.

FIGURE 1. Flow visualization of the vortex formation and near-wake flow for a circular cylinder at a Reynolds number $Re = 200$. The wake was visualized by introducing a sheet of aerosol particles into the wind tunnel contraction section (Griffin & Votaw 1972; Griffin & Ramberg 1974). The cylinder is oscillating at an amplitude of $a/d = 0.15$ and a frequency $f = 0.85f_{so}$ (f_{so} is the Strouhal frequency).

3. The near-field flow

The fluctuation u_{rms} of the x-component of velocity on the wake centreline is plotted in figure 2(*b*) with distance downstream from the cylinder, as measured in multiples of the cylinder diameter d. This is from a two-dimensional spectral element computation reported by Hall & Griffin (1993). The corresponding mean velocity on the wake centreline is plotted in figure 2(*a*). The computed peak in u_{rms} is located at about $1.25d$ downstream from the centre of the cylinder, which is comparable to other recent two-dimensional discrete vortex computations ($x = 1.5d$) at the same Reynolds number of 200 (Meneghini & Bearman 1993). At the end of the formation region the time-averaged velocity U has reached 30% of the free-stream value.

Laboratory measurements of the formation region, e.g. from Griffin (1971, 1974), are greater in streamwise extent as shown in figure 3 and in the subsequent discussion. The velocity traverses in the cross-stream and downstream directions at $Re = 200$ in figure 3 are illustrative of the definitions (iii) and (iv) given above, and agree quite well with others that are illustrative of (ii). The same change in the formation region length with the frequency of the cross-stream cylinder oscillations was computed by Meneghini & Bearman (1993).

In the modified low Reynolds number vortex formation model of Green & Gerrard (1993), shed vorticity accumulates in the wake while diffusive mixing of oppositely signed vorticity causes a net loss of the latter. Meanwhile the equal and opposite shedding of circulation on the two sides of the wake remains constant. The region close to the cylinder base is one of high shear stress, from which convection and diffusive transport combine to build a growing vortex further downstream. The feeding of vorticity downstream and the induction of cross-stream flow within the formation region provide a *Re*-dependent balance in the wake. This overall process occurs in two stages, the first being vortex formation with downstream distance followed by the actual periodic shedding of vortices.

The *Re*-dependence of the Strouhal number *St* as measured by Roshko (1954,

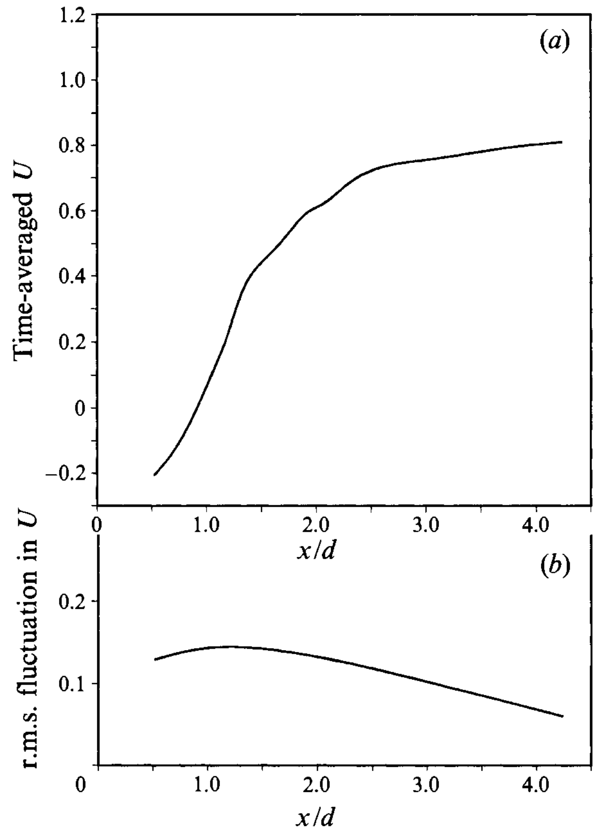

FIGURE 2. Spectral element computation of the flow field in the near wake of a stationary circular cylinder at a Reynolds number, $Re = 200$. (*a*) Time average of the velocity U on the centreline of the wake. (*b*) Root-mean-square u_{rms} of the velocity U on the centreline of the wake.

1955), Gerrard (1978), and Williamson (1988, 1989) coincides with the change in vorticity transport and vortex formation at the low Re below 350. The shear stress contribution diminishes in importance with increasing Re, so that the shedding frequency is governed solely by the induced velocity field of the near wake at the higher Reynolds numbers (above 350).

The development of the near-field flow in the wake of a circular cylinder is shown in figure 4, which is modified from the original given by Green & Gerrard (1993). The initial appearance of the near wake vorticity that is eventually shed, as measured by Green & Gerrard, is not influenced by the Reynolds number and remains close to the cylinder base, near $x = 0.8d$. The previous low-Re measurements by Gerrard (1978) mark the initiation of shedding as indicated by dye injection in water, not the fully formed vortex, and are equivalent to this initial appearance of vorticity in the near wake as measured by Green & Gerrard.

Several low-Re measurements of the vortex formation region length, as represented by the positions of the maximum velocity fluctuation, are plotted in figure 4. The measurements by Shaefer & Eskinazi (1959) and by Nishioka & Sato (1978) represent the off-centreline maximum of the velocity fluctuation, at the fundamental or Strouhal frequency. The measurements by Griffin (1971, 1974), and by Griffin & Ramberg (1974) represent the position of maximum velocity fluctuation on the wake centreline

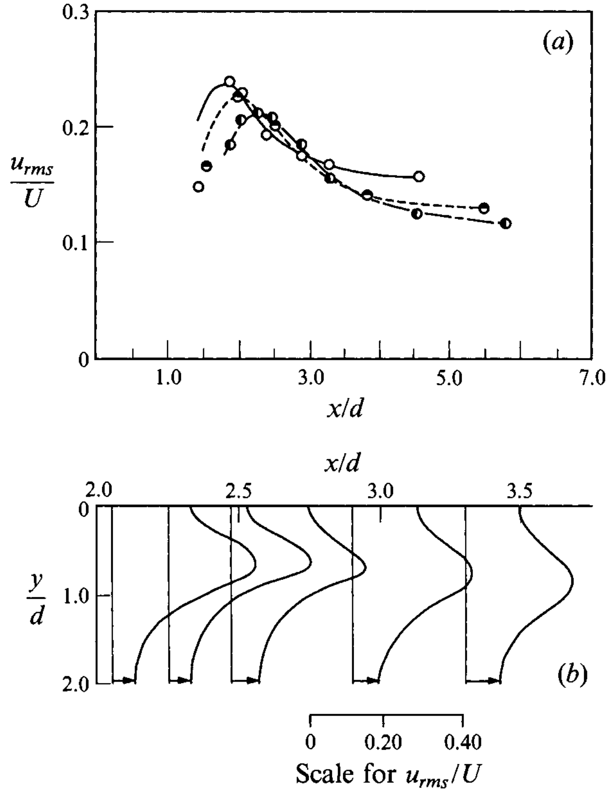

FIGURE 3. Root-mean-square u_{rms} of the velocity U measured in the near wake of a circular cylinder at a Reynolds number, $Re = 200$. (*a*) r.m.s. of the velocity on the wake centreline for a cylinder oscillating at an amplitude of $a/d = 0.15$, and three frequencies of $f = 0.89f_{so}$ (◐), $0.93f_{so}$ (◓), $1.0f_{so}$ (○). Here f_{so} is the natural or Strouhal shedding frequency. (*b*) Development of the r.m.s. velocity fluctuation field near the end of the vortex formation region of an oscillating cylinder, for $a/d = 0.15$, $f = 0.89f_{so}$.

up to $Re = 350$, at twice the Strouhal frequency. All of the experiments just discussed correspond to the definitions (ii) and (iii) given above. The definition (iv) based on the cross-stream spacing d' of the maxima of u (the wake width) also agrees with these experiments, as shown by Shaefer & Eskinazi (1959) and Griffin (1971, 1974).

There is some scatter among the results from the experiments in figure 4, and this is worthy of brief discussion. Error bounds of 10% have been applied as an example to the results of Griffin (1971, 1974), though the actual errors were less than this estimate. For Reynolds numbers from $Re = 120$ to 160 the total scatter among the results marking the end of the formation region extends over approximately 30%. However, the results of Griffin (1971, 1974) and of Griffin & Ramberg (1974) agree very well with those of Green & Gerrard (1993). All of the measurements of the vortex formation region length are scaled by the cylinder diameter d. The agreement between Green & Gerrard and the experiments of Schaefer & Eskinazi (1959) and Nishioka & Sato (1978) is reasonable but with greater scatter among the results. One reason for the difference between experiments is the inaccuracy in identifying the end of the formation region because of the relatively broad downstream extent of the minimum between the regions of off-centreline maximum velocity fluctuation (Bearman 1965; Schaefer & Eskinazi 1959).

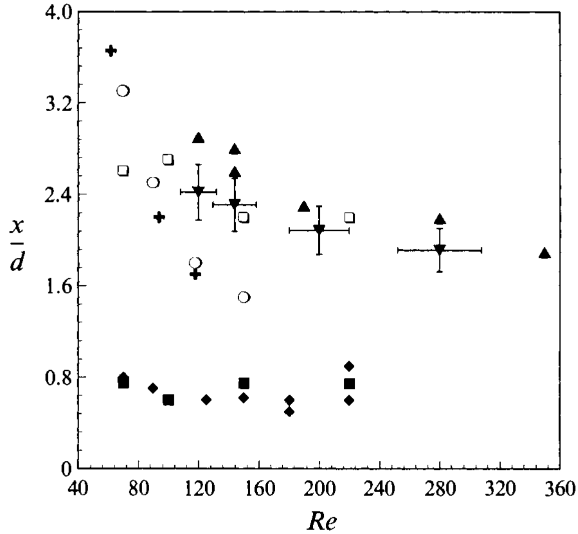

FIGURE 4. Development of vortex street formation in the near wake of a circular cylinder as a function of the distance x/d downstream of the base of the cylinder, and the Reynolds number Re. Green & Gerrard (1993): ■, formation of separated area of vorticity which is eventually partially shed; □, position of vortex centre when beyond the shear stress region and, also, the position of maximum vortex strength. Gerrard (1978): ◆, the formation region length from dye injection. Schaefer & Eskinazi (1959): +. Nishioka & Sato (1978): ○, position of maximum longitudinal velocity amplitude (off the wake centreline) at the *fundamental* shedding (Strouhal) frequency. Griffin (1971, 1974): ▼. Griffin & Ramberg (1974): ▲, position of maximum longitudinal velocity amplitude (on the wake centreline) at *twice* the shedding (Strouhal) frequency.

The experimental estimates of the length of the formation region from the wake velocity traverses extend downstream beyond those which are derived from the two-dimensional computations. This is most likely caused by the three-dimensional effects and related disturbances which are inherent in the experiments. The importance of considering three-dimensional effects and methods for minimizing them by such means as end plate orientation have been discussed by Williamson (1989). The wake also can be stabilized and its parallel shedding or two-dimensional behaviour enhanced by cylinder oscillations or other external disturbances which produce vortex shedding lock-on (Griffin & Hall 1991).

The positions of maximum vortex strength deduced by Green & Gerrard from their particle streak measurements of velocity and vorticity in the near wake of the cylinder generally agree with these several independent estimates of the vortex formation region length, for Re up to 220 as shown in figure 4. The coincidence of the maximum vortex strength with the end of the formation region can reasonably be extended to $Re = 350$, because the basic vortex shedding mechanism remains the same up to that Reynolds number.

4. Summary

Low Reynolds number (less than $Re = 350$) and high Reynolds number (greater than $Re = 350$) mechanisms of bluff body vortex formation have been described in the literature over the past forty years. The recent experiments of Green & Gerrard (1993) have demonstrated fairly conclusively that the end of the vortex formation region coincides with the overall location in the wake at which the vortex strength is a maximum. This coincidence of the wake properties has been inferred by numerous researchers, but until now it has not been measured or computed in a fully satisfactory way.

The results presented in this note reconcile the several definitions put forward for the streamwise extent of the vortex formation region. Three of these which are based upon the properties of the near-wake velocity field agree reasonably well with each other to within the experimental scatter for Reynolds numbers up to 350. The formation length or the effective position of shedding by any of these measures in turn agrees with the location of maximum vortex strength as estimated by Green & Gerrard (1993) from their experiments.

The puzzle of the bluff body near wake has eluded full solution by many researchers over several decades. These experiments will play an insightful role in future stability analyses, computations, and experiments not only into stationary bluff body wake dynamics, but into the effects of various forms of external control disturbances as well. For recent examples of the latter see, for example, Griffin & Hall (1991), Meneghini & Bearman (1993), and Roussopoulos (1993).

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